Zeeman slowing atoms using the magnetic field from a magneto-optical trap

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We study a Zeeman slower using the magnetic field generated by a pair of coils for a magneto-optical trap. The efficiency of the Zeeman slower is shown to be dependent on the intensity and frequency detuning of the laser light for slowing the atoms. With the help of numerical analysis, optimal experimental parameters are explored. Experimentally, the optimal frequency detuning and intensity of the slowing beam are explored, and 4×10^7 ytterbium atoms are trapped in the magneto-optical trap.

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The technique of laser cooling[1] opens up the possibility to cool atomic samples down to temperatures near absolute zero. Since laser-cooled atoms have low velocity and good coherence, they have enabled the observation of a new state of matter (Bose–Einstein condensate), the improvement of spectroscopic measurement, quantum information, and the realization of even more accurate atomic clocks[2–6].

As one of the standard techniques for slowing an atomic beam, the Zeeman slower reduces the velocity of atoms from a few hundred meters per second (m/s) to tens of m/s[7,8]. In a Zeeman slower, atoms absorb red-detuned photons propagating from the opposite direction, where the Doppler frequency shift $\overrightarrow{k}\cdot\overrightarrow{v}$ compensates the laser frequency detuning from the resonance. Although the velocity of atoms is reduced after they absorb photons, the atoms keep absorbing counter-propagating photons by shifting the resonance frequency of the atoms in a specially designed magnetic field to assure efficient slowing. Typically, the magnetic field is produced by a solenoid coil with a length of tens of centimeters and extra water cooling. In some applications requiring compact size and less weight (e.g., aerospace applications), permanent magnets have been used[9].

Here, we analyze a Zeeman slower, where the magnetic field for shifting the atomic resonance is produced by an anti-Helmholtz coil, which also produces the magnetic field for a magneto-optical trap (MOT). This scheme can simplify the system and reduce the size and mass of the slower, although it is less efficient than the traditional slower. The initial idea is from Refs. [10] and [11], while in this Letter we study the principle of this technique. Moreover, the effect of the experimental parameters, such as laser frequency detuning and intensity of the slowing beam, are explored by numerical analysis for trapping more atoms in the MOT. In the experiment, 4×10^7 ytterbium atoms are successfully slowed and finally trapped in the MOT using this scheme.

As shown in Fig. 1, the magnetic field for slowing atoms is simply produced by an anti-Helmholtz coil. For a single coil with radius R_c perpendicular to the y axis and centered at $y=A$, the axial field along the z axis is[12]

$$\overrightarrow{B}(z)=\frac{\mu_0 I}{2\pi z}\frac{-A}{\sqrt{(R_c+z)^2+A^2}}\times[-K(k^2)] + \frac{R_c^2+z^2+A^2}{(R_c-z)^2+A^2}E(k^2), \quad (1)$$

where $\mu_0=4\pi\times10^{-7}\ \mathrm{N\cdot A^{-1}}$, I is the current through the coil, and the argument of the complete elliptic integrals K and E is $k^2=4R_c z/[(R_c+z)^2+A^2]$. Figure 1 also shows the magnetic field $\overrightarrow{B}(z)$ along the z axis generated by a pair of coils with $I=100$ A, $R_c\sim$4.5 cm, and

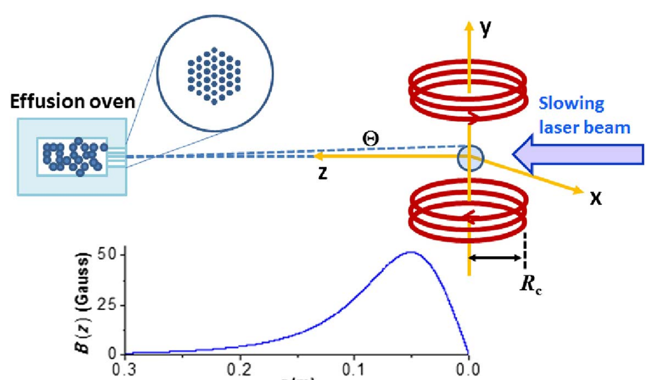

Fig. 1. Schematic of the Zeeman slower, whose magnetic field is generated by a pair of coils with 32 turns for the MOT. At the bottom, it shows the magnetic field produced by the anti-Helmholtz coil. The inset shows the geometry of the output holes.

$A \sim 8$ cm (32 turns). Interestingly, in the region from $z = 0$ to 30 cm, the magnetic field is similar to that generated by a solenoid coil in a standard Zeeman slower, so it is possible to slow atoms without extra setups to generate the magnetic field.

Next, we analyze the effect of this deceleration system. Due to the Zeeman effect, the angular frequency shift of the atoms in the magnetic field $\vec{B}(z)$ is $\vec{\mu} \cdot \vec{B}(z)/\hbar$, where $\vec{\mu}$ is the magnetic moment of the atoms, $\vec{\mu} = -\mu_B g \vec{J}/\hbar$, μ_B is the Bohr magneton, $\vec{J}$ is the total electronic angular momentum, and g is the Landé g-factor. Assume a slowing laser beam with detuning angular frequency of Δ counter-propagates with the atomic beam. The angular frequency detuning seen by the atoms with velocity $\vec{v}$ is

$$\delta = \vec{k} \cdot \vec{v} + \Delta + \frac{\vec{\mu} \cdot \vec{B}(z)}{\hbar}, \tag{2}$$

where $\vec{k}$ is the wave vector of the slowing laser light.

When the atoms absorb the photons from the slowing beam, the force exerted on the atoms is[13]

$$\vec{F} = -\hbar \vec{k} \frac{\Gamma}{2} \frac{s}{1 + s + (2\delta/\Gamma)^2}. \tag{3}$$

Here, Γ is the decay rate of the transition. The saturation parameter is $s = I_{\text{slow}}/I_s$, where I_{slow} is the intensity of the slowing laser beam, and I_s is the saturation intensity of the atomic transition. The force slows the atomic velocity as $\vec{F} = m\frac{\mathrm{d}\vec{v}}{\mathrm{d}t}$, where m is the atomic mass.

According to the effusive beam theory, the velocity distribution of thermal atomic beam $f(v)$ has a Maxwell–Boltzmann (M-B) distribution as[14]

$$f(v) = \frac{v^3}{2\check{v}^4} \exp\left(-\frac{v^2}{2\check{v}^2}\right), \tag{4}$$

where $\check{v} = \sqrt{k_B T/m}$, k_B is the Boltzmann constant, and T is the temperature of the atoms. The red dashed line in Fig. 2 shows the velocity distribution of the atoms flying from an oven with $T = 653$ K along the $-z$ axis.

When the atoms in the magnetic field $\vec{B}(z)$, as shown in the bottom of Fig. 1, interact with the slowing laser light with the frequency detuning of $\Delta/(2\pi) = -135$ MHz and the saturation parameter of $s = 0.35$, the velocity distribution of the slowed atoms can be numerically calculated, shown with the blue solid line in Fig. 2. The atoms with the initial velocity below 100 m/s are efficiently slowed.

Assume that the MOT traps all atoms that enter the trapping region with a velocity less than the maximum capture velocity v_c, which is given by[15]

$$v_c = \frac{8 d \hbar k^2}{3m} \frac{I_{\text{trap}}}{I_s} \frac{\Delta_T}{\Gamma} \left(1 + \frac{I_{\text{trap}}}{I_s} + 4\frac{\Delta_T^2}{\Gamma^2}\right)^{-2}, \tag{5}$$

where d is the diameter of the trap beam, I_{trap} is the total intensity of all six MOT beams, and Δ_T is the frequency

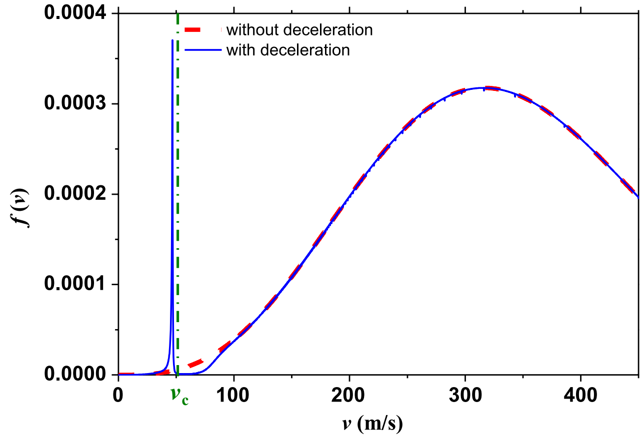

Fig. 2. Velocity distribution of the thermal atomic beam without deceleration (red dashed line) and with deceleration (blue solid line). The green dashed and dotted line shows the capture velocity of the MOT.

detuning of the trap beam. Here, we take ^{171}Yb atoms as an example. The transition for slowing and trapping is $^1S_0 \rightarrow {}^1P_1$, which is at 399 nm and has a decay rate of $\Gamma = 2\pi \times 28$ MHz. If the diameter of the trapping beam d is 20 mm, the power for each beam is 10 mW, the frequency detuning is -30 MHz, and the maximum capture velocity is $v_c \sim 49.6$ m/s, as shown with the green dashed and dotted line in Fig. 2. After integrating the velocity distribution when the velocity is from 0 to v_c, almost 1.2% from the total atoms are trapped, compared to 0.069% without deceleration. That means this slower can increase the trapped atomic number by nearly 17 times.

In Eq. (3), it shows the frequency and the intensity of the slowing beam affect the deceleration force and thus the final atomic number in the MOT. We studied the dependence of the atomic number trapped in the MOT on the saturation parameter s and laser frequency detuning $\Delta/(2\pi)$ of the slowing beam. The simulation results are shown in Fig. 3. In Fig. 3(a), for each Δ, the number of the trapped atoms increases with the saturation parameter s. When s is small, e.g., $s = 0.07$, for a smaller $|\Delta/(2\pi)|$, more atoms are trapped. In contrast, when $s > 0.1$, the MOT traps even more atoms when the slowing light has a larger frequency detuning. In Fig. 3(b), for each saturation parameter s, the slowing laser light has a different optimal frequency detuning for a maximum trapped atomic number.

We also estimate the absolute number of the trapped atoms according to the experimental setup. In the experiment, the atomic beam is generated from an effusion oven heated at $T = 653$ K. The saturated vapor pressure P_0 inside the oven can be estimated from the oven temperature T according to $\log(P_0) = 14.117 - 8111/T - 1.0849 \times \log(T)$[16], which is 4.4×10^{-2} Pa.

In this Letter, there are 37 holes with a radius $r = 0.2$ mm and a length $l = 5$ mm between the oven and the MOT region for collimating the atom beam, shown

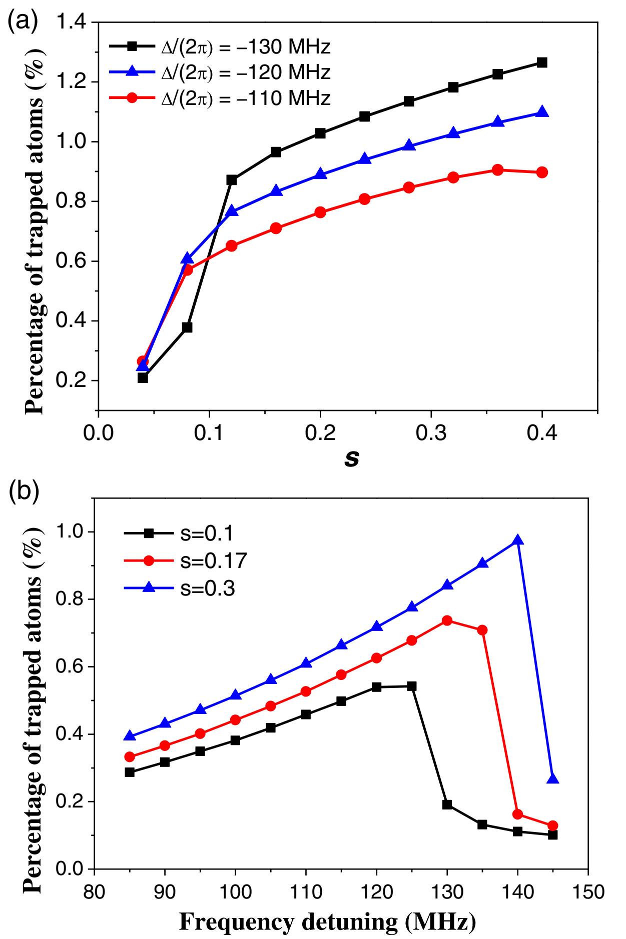

Fig. 3. Simulation result. (a) The percentage of trapped atoms increases with the saturation parameter s when the frequency detuning $\Delta/(2\pi)$ of the slowing beam is −110 MHz (red dots), −120 MHz (blue filled triangles), and −130 MHz (black filled squares), respectively. (b) The percentage of trapped atoms depends on the frequency detuning $\Delta/(2\pi)$ of the slowing beam at different saturation parameters.

in the inset of Fig. 1. The rate of atoms output from one hole can be estimated from[17]

$$n_o = \frac{2N_A \pi r^3}{3}\sqrt{\frac{8RT}{\pi M}}\frac{\Delta P}{lRT}, \tag{6}$$

where N_A is the Avogadro constant, R is the gas constant, M is the molar mass, and ΔP is the pressure difference between the two sides of the output holes. Usually, the pressure at the MOT side is about 10^{-7} Pa. From Eq. (6), the total rate of ^{171}Yb atoms output from the oven is $n_o = 2.4\times10^{13}$/s, considering the abundance of ^{171}Yb atoms.

The atomic beam flux intensity j (in unit of $s^{-1}\cdot sr^{-1}$) near the center line is given by[18]

$$j = \frac{n_o}{\pi W}, \tag{7}$$

where $W = (8r/3l)/(1+8r/3l)$. The solid angle Θ covered by the slowing beam is 3.14×10^{-4} sr according to the beam size of the slowing beam and the distance between the MOT region and the oven in this Letter. Therefore, the rate of the atoms flying to the MOT region is $n = 2.5\times10^{10}$/s.

From the simulation result, when the atoms propagating from the oven ($T = 653$ K) interact with the slowing beam with $\Delta/(2\pi) = -130$ MHz and $s = 0.35$, the percentage of the atoms trapped in the MOT with maximum capture velocity of 49.6 m/s is 1.2%. Therefore, the atomic capture rate of the MOT is $R_c = 2.5\times10^8$/s. The number of atoms captured in the MOT at time t can be estimated from[19]

$$N(t) = R_c\tau\left[1-\exp\left(-\frac{t}{\tau}\right)\right], \tag{8}$$

where τ is the MOT lifetime, determined by the collision between the trapped atoms and between the trapped

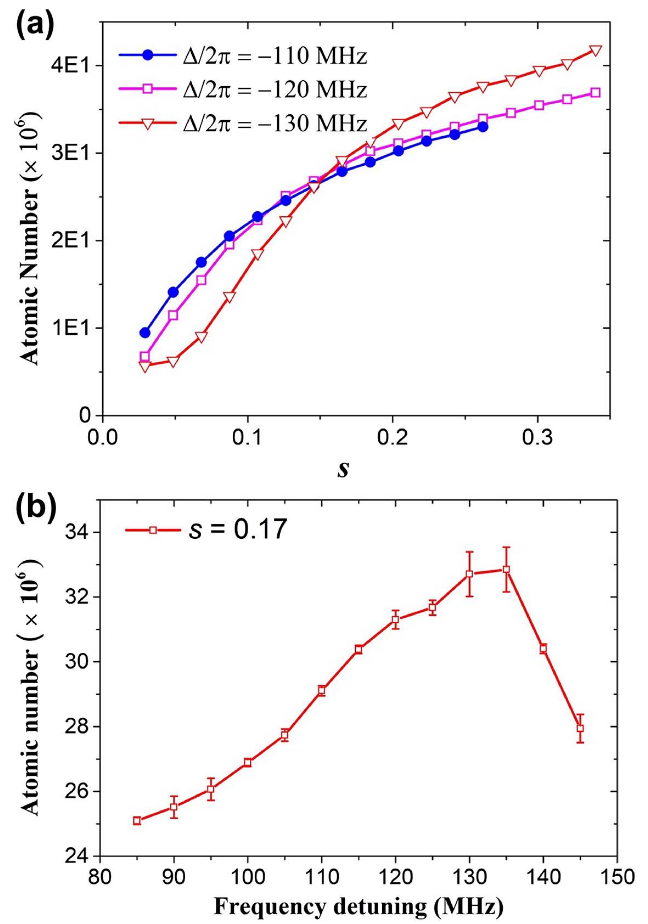

Fig. 4. Experimental result. (a) The number of trapped atoms increases with the saturation parameter s when the frequency detuning $\Delta/(2\pi)$ of the slowing beam is −110 MHz (blue dots), −120 MHz (magenta open squares), and −130 MHz (red open triangles), respectively. The oven temperature is $T = 653$ K. The measurement error is about 1% based on ten measurements. (b) The number of trapped atoms depends on the frequency detuning $\Delta/(2\pi)$ of the slowing beam when the saturation parameter is 0.17.

atoms and the background gas. In this Letter, the MOT lifetime τ is measured to be 0.5 s. When $t \gg \tau$, the number of the atoms finally trapped in the MOT is estimated to be 1.3×10^8 according to Eq. (8).

In the experiment, the atoms are output from the oven with a temperature of 653 K. The magnetic field for the Zeeman slower is generated by the anti-Helmholtz coil, which is shown in Fig. 1. The laser for trapping the atoms is separated into three beams. In each beam, the light has a power of 10 mW. We measured the number of trapped atoms in the MOT as a function of saturation parameter s and frequency detuning $\Delta/(2\pi)$ of the slowing beam, as shown in Fig. 4. When the laser light for slowing the atoms has a frequency detuning of -130 MHz and intensity of $20\ \mathrm{mW/cm^2}$, corresponding to a saturation parameter $s = 0.35$, the atomic number is measured to be 4×10^7 from a photomultiplier tube (PMT) that collects the fluorescence of the atoms.

The number of the atoms trapped in the MOT is three times smaller than that estimated from the simulation results. The discrepancy largely arises from the imperfect spatial overlap between the slowing beam and the atomic beam. In addition, the intensity of two counter-propagating MOT laser beams in each direction is unbalanced due to the loss of vacuum windows, leading to an unbalanced force on the atoms. Moreover, the transmission loss of the window for transmitting the slowing beam is neglected in the simulation, which can be as large as 20% due to atomic deposition on the window.

Further improvements on increasing the number of trapped atoms in the MOT can be realized by several ways. By increasing the oven temperature from 653 K to 673 K, the rate of atoms output from the oven will be increased by 2.5 times. When using collimating holes with $r = 0.1$ mm and a length $l = 8$ mm, the rate of atoms entering the trapping region will be increased by three times. By reducing the distance between the oven and the MOT, the number of trapped atoms can also be increased.

In conclusion, we build a Zeeman slower with the magnetic field produced by an anti-Helmholtz coil in the MOT. The optimal laser frequency detuning of the slowing beam with attainable intensity is explored both in numerical analysis and in the experiment. Using this method, 4×10^7 ytterbium atoms are successfully slowed and trapped in the MOT. This kind of design can be applied in the portable cold atomic system and atomic clocks in space. The atomic number trapped in the MOT will be increased if further improvements on the experimental setup are made.

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